# A View of Hurricane Katrina with Early 21st Century Technology

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## Abstract

Recent advances in space-borne observations and numerical weather prediction models provide new opportunities for improving hurricane forecasts.

In this study, state-of-the-art satellite observations are used to document the evolution of one of the most devastating tropical cyclones ever to hit the United States: Hurricane Katrina. The ECMWF and NASA global high-resolution forecasts, the latter being run in experimental mode, are compared with satellite observations, with a focus on precipitation and cloud processes. Future directions on modeling and observations are briefly discussed.

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# 1. Introduction

Over one hundred years ago, the Galveston Hurricane, an estimated Category 4 storm, made landfall on the city of Galveston, Texas. The hurricane nearly wiped out the entire city, and about 8000 people died, making the storm the deadliest natural disaster ever to strike the United States (http://www.noaa.gov/galveston1900). At that time, only scattered ship reports could provide some very limited information for hurricanes at sea, and there were no visible monitoring or warning capabilities, let alone prediction capabilities, of the hurricane's track and intensity.

Our observing, modeling and forecasting systems have been undergoing rapid development in the past 2-3 decades. For example, Atlantic Hurricanes are closely monitored by scientists at National Weather Service of US National Oceanic and Atmospheric Administration (NOAA) through a significantly improved upper-air, and ground-based observational network supplemented by aircraft, ship and ocean buoy data. Given initial conditions and lateral boundary conditions provided by larger-scale model analyses, regional, mesoscale-resolving models have been widely utilized to predict the hurricane's track and intensity. Nowadays, (1) satellite observations play an increasingly important role in providing global estimations of precipitation, top-of-the-atmosphere radiative fluxes, clouds, temperature, and winds, as well as aerosols, with un-precedented temporal and spatial coverage. Extensive efforts are being made to retrieve vertical profiles of latent and radiative heating and in-cloud hydrometer properties; (2) global atmospheric models and global operational analyses are moving toward to providing forecasts and products at resolutions ranging from 0.1° to 0.5° (10-50 km). There is evidence that improved hurricane structure and path forecasts could partially result from such increases in model resolution (e.g., Shen et al., 2006). These advances in global modeling may eventually eliminate the need for regional hurricane forecasts, and the associated concerns with the need to specify lateral boundary conditions; yet they also raise interesting challenges to atmospheric modeling and parameterization communities since at these resolutions some assumptions made in the model's sub-grid scale parameterizations are only marginally valid. Evaluating these new developments in global models and observing systems particularly their representation of physical and dynamical processes affecting hurricanes, is a necessary and important step toward improving hurricane forecasting.

In this study, high-resolution satellite observations of rainfall, clouds, wind, and sea surface temperatures (SST) are analyzed to document the evolution of Hurricane Katrina as well as to illustrate the potential of the tremendous technological and scientific advances made in the intervening century since the 1900 Galveston Hurricane. Katrina was one of the most devastating tropical cyclones ever to hit the United States, with an official death toll of more than 1300 and an estimated damage of more than $200 billion. Even though it weakened from Category 5 to strong Category 3 before making landfall (Knabb et al. 2005), Hurricane Katrina produced massive damage in Louisiana, Mississippi and Alabama, and severely affected millions of people. In the interest of highlighting present-day global model forecasting capabilities, our analysis uses the European Centre for Medium Range Forecast (ECMWF) global forecasts and the

National Aeronautics and Space Administration (NASA) Goddard Earth Observing System Version 5 (GEOS-5) global forecasts alongside satellite observations, with a focus on precipitation and cloud processes. Summarizing remarks include discussions of expected areas of future research.

## 2. Observations

Microwave rainfall retrievals from a five-satellite constellation, including the Tropical Rainfall Measurement Mission (TRMM), the Defense Meteorological Satellite Program (DMSP) F13, F14 and F15, and the Earth Observing System (EOS) Aqua satellite, are merged in this study to provide global, 6-hour coverage. The rainfall retrievals used here are all based on the most recent version of the NASA Goddard Profiling (GPROF) algorithm [Kummerow et al. 2001; Olson et al. 2006]. They are further supplemented by AMSU-B rainfall retrievals from NOAA 15, 16 and 17, and are verified with surface rain gauge and precipitation radar data.

Cloud-top and cloud optical properties (at 0.25°x0.25° resolution) are computed from pixel data collected by the Moderate Resolution Imaging Spectroradiometer [MODIS, King et al. 2003] on two EOS sun-synchronous satellites Terra and Aqua. Cloud ice measurements (at 8°x4°) are from EOS Microwave Limb Sounder (MLS) onboard the Aura satellite (Waters et al. 1999, Li et al. 2005). Daily TRMM Microwave Imager (TMI)-derived 0.25°x0.25° SSTs, and QuikSCAT 0.25°x0.25° ocean wind vectors, are also used in our analyses.

## 3. Models and forecasts

The 5-day operational forecasts at T799 spectral resolution (approximately 25 km equivalent) from the ECMWF Integrated Forecasting System (IFS) are used. The atmosphere is divided into 60 vertical layers. A mass flux convective scheme developed by Tiedtke (1989) and later modified as in Gregory (2000), is used to simulate convection. The cloud parameterization used in the forecasts has two prognostic equations for cloud water (ice+liquid) and cloud cover [Tiedtke 1993, Jakob 1999], which both have an explicitly modeled convective source. The forecasts are initialized with the ECMWF 4-dimensional variational analyses.

The NASA GEOS-5 AGCM uses a finite-volume dynamical core [Lin and Rood 1996, 1997]. The moist parameterization includes the relaxed Arakawa-Schubert convective parameterization [Moorthi and Suarez 1992] coupled with a fully prognostic cloud condensate scheme with liquid and ice phases. Cloud fractions are estimated using a sub-grid probability distribution function of total water which incorporates detraining mass and condensate from convection (Bacmeister 2006). The model's prognostics and diagnostics are computed at 0.25°x0.33° resolution in the horizontal, and 72 layers in the vertical, extending from the surface to 0.01 hPa. The forecast presented here is from a 5-day experimental run initialized with the National Center for Environmental Prediction (NCEP) T382 analysis.

## 4. The satellite view of Katrina

Six-hour averaged rain rates centered at 1800 UTC from August 23 to 30, 2005 are shown in Figure 1. Katrina originated over the southeastern Bahamas on August 23, 2005 (Fig.1a). It strengthened into Tropical Storm Katrina the next day and gradually moved westward, making landfall on the southeastern coast of Florida at about 2300 UTC, on the 25th. During this period, the Gulf of Mexico was dominated by clear-sky conditions with scattered, isolated clouds (not shown). SSTs averaged over the central Gulf region (24°N-29°N, 92°W-85°W) were warm, generally above 30°C on the 25th and slowly increasing up to 30.6°C on the 27th (Fig. 2a). These provided favorable conditions for enhanced deep convection and a strengthening of the hurricane.

After passing southern Florida as a weak Category 1 hurricane, Katrina intensified rapidly over the warm waters of the Gulf of Mexico between August 26 and 28 (Figs. 1d, 1e, and 1f), with estimated highest sustained winds of 175 mph (78 m/s) [Knabb et al. 2005]. Convection and clouds became more organized in a spiral pattern, and precipitation was more widespread and intensive, with the heaviest rain rate over 10 mm/h near the eye wall. Merged microwave rain retrievals, MODIS cloud-top temperature and cloud optical thickness, averaged between 24°N-29°N, and 92°W–85°W, correspond nicely with one another (Fig. 2a and 2b). Although the wind retrievals are underestimated due to the rain contamination, QuikSCAT data indicated ocean surface wind speed above 30 m/s around the hurricane center (Fig. 2d). SSTs averaged along the hurricane track started to decrease after the passage of Katrina, and the lowest SST (28.6°C) occurred about 3-4 days later when Katrina had already made landfall, suggesting a strong upwelling of deeper, cooler ocean water resulting from strong mixing induced by the hurricane (Price, 1981).

Katrina made landfall near the Louisiana-Mississippi border at about 1200 UTC 29 August, and started to weaken as it moved northward and inland (Fig. 1g). However, the hurricane was still a large system, and precipitation was still heavy and widespread with the heaviest rain rate over 5 mm/h around the center. By 1800 UTC on the 30th (Fig. 1h), Katrina had weakened into a tropical depression. During this time, local SSTs along the hurricane track over the Gulf of Mexico decreased by 3-5°C compared to the pre-hurricane SSTs (Fig. 2c) before slowly recovering on the 31st. After 30 August, the Katrina-related rain band moved to mid-latitudes, and merged with an extra-tropical wave to become a mid-latitude frontal rain band.

## 5. Comparison of early model forecasts with satellite data

Evaluation of hurricane forecast skill requires ensembles of historical forecasts. A preliminary examination of ECMWF and NASA global high-resolution forecasts indeed suggest that at shorter lead times, both have comparable track forecast errors as the National Hurricane Center (NHC) average official forecast track errors for Katrina. Our purpose, however, is not to undertake such an evaluation here, but rather demonstrate the current status of satellite physical retrievals and their potential to provide valuable information for such evaluations and so contribute to model improvements. We show in

Figure 3 a pictorial example of the 120-hr accumulated surface rainfall from satellite retrievals, and from single high-resolution forecasts from ECMWF and NASA models. The observed hurricane track (black line) is the NHC's official best track. The forecast initial conditions, 12Z and 06Z August 25 for the ECMWF and NASA models respectively, about half a day before Tropical Storm Katrina made landfall in Florida, were selected so that both the intensification over the Gulf of Mexico and weakening after making landfall in Louisiana could be examined. The model hurricane tracks (blue lines) are estimated based on the forecast sea level pressure and wind fields.

Predictions of Hurricane Katrina were statistically better than the historical forecast skill (e.g., Knapp et al. 2005). Consistent with this, both ECMWF and NASA high-resolution forecasts perform remarkably well during the first 2 days, with the forecast tracks closely matching the observed, and only small displacement errors. Instead of being near the storm center, the heaviest model rainfall during the first 48 hours is about 80-120 km to the south of the hurricane track, similar to what was observed. This interesting feature can not be identified by examining the dynamical fields alone. Overall, the amplitude of the model accumulated rain amount is similar to satellite microwave retrievals, although the ECMWF (GEOS) model shows a slightly higher (lower) amount. Track displacements start to amplify in the 96-120hr forecasts, but the errors are still in line with the mean errors by the NHC official forecasts. The simulated Katrina in the NASA model tends to move more slowly, and remains over the Gulf of Mexico. The forecasted track deviates by 2-3 degrees west of the best track. On the other hand, the hurricane in the ECMWF forecast deviates by 2-3 degrees east of the best track, and makes landfall between Alabama and Florida about 12 hours late. These differences in the hurricane track and accumulated precipitation may reflect inadequacies in the large scale circulation provided in the initial conditions, or imperfect model physical parameterizations, but may also be due simply to the system's lack of predictability.

Given the tremendous difficulties in adequately characterizing the cloud hydrometeor profiles from space, comparisons of model cloud ice water content (IWC) with observations [e.g., Li et al. 2005], especially at the hurricane scale, have been few. A comparison of the two forecasts with MLS IWC in the upper troposphere (Fig. 4), in which MLS data have to be shown in their native coarser resolution, indicates that the amplitudes and distributions of IWC from both model forecasts and MLS observations are in a good qualitative agreement. Both ECMWF and NASA forecasts show two maxima along their hurricane tracks with IWC above 18 mg/m$^3$, while MLS shows one broad maximum with IWC between 14 and 16 mg/m$^3$. The largest disagreement is near the south coast of Louisiana. Further improvements in the horizontal and vertical resolution are a high priority for follow-on MLS-like missions and the CloudSat mission launched on 28 April this year. Both are expected to provide more comprehensive and important cloud validation information for the GCM forecasts.

## 6. Summary and Discussions

Historically, due to the lack of reliable observations on precipitation and clouds, studies of hurricane forecasts have mainly focused on dynamical fields such as sea level pressure

and wind. The recent advances in observing, modeling, and forecasting systems have allowed direct comparisons of global high-resolution model forecasts of hurricanes against satellite retrieved fields of precipitation and clouds at un-precedented temporal and spatial scales. In this study, the evolution of one of the most devastating tropical cyclones ever to hit the United States, Hurricane Katrina, is documented using concurrent satellite data. ECMWF and NASA GEOS5 global high-resolution forecasts of Katrina are compared against state-of-the-art satellite observations of precipitation and cloud properties. Both models exhibit very encouraging forecast capabilities of the hurricane track during the first 48-72 hours, and the 5-day accumulated rain amount and upper-troposphere cloud ice water content show good qualitative agreements with observations.

Apart from their importance for NWP, global atmospheric models of hurricanes and their forecasts represent an important and unique test bed of model formulations. Recent improvements that include moving from synoptic-scale-resolving to mesoscale-resolving global models show some very encouraging results. In addition to increasing resolution, and including more physically-based parameterizations on mesoscale effects in conventional GCMs, cloud-scale-resolving global models, in which the cloud dynamics and mesoscale processes are explicitly resolved, are also being developed [e.g., Randall et al. 2003] and could be used as a parallel approach to more realistically simulate hurricane clouds in global models in the future. It is expected that by well resolving the hurricane structure and larger scale steering circulation, along with improved initial conditions provided by high resolution satellite data and sophisticated data assimilation systems, these exciting advances in observing technology and models will lead to better detection, monitoring, understanding and prediction of the genesis and development of hurricanes that have such a devastating impact on our society.

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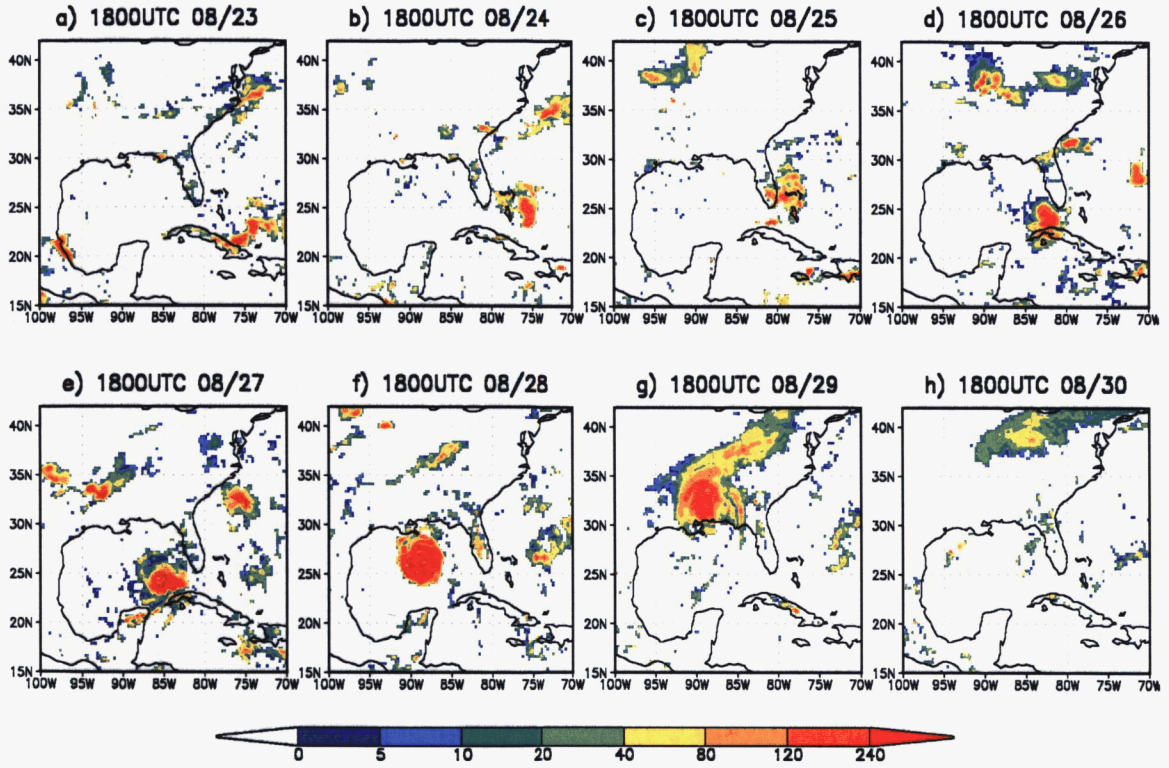
Figure 1: Horizontal distributions of 6-h averaged microwave rainfall retrievals (mm/day, 0.25x0.25 deg.) centered at 1800 UTC from August 23 to 30, 2005.
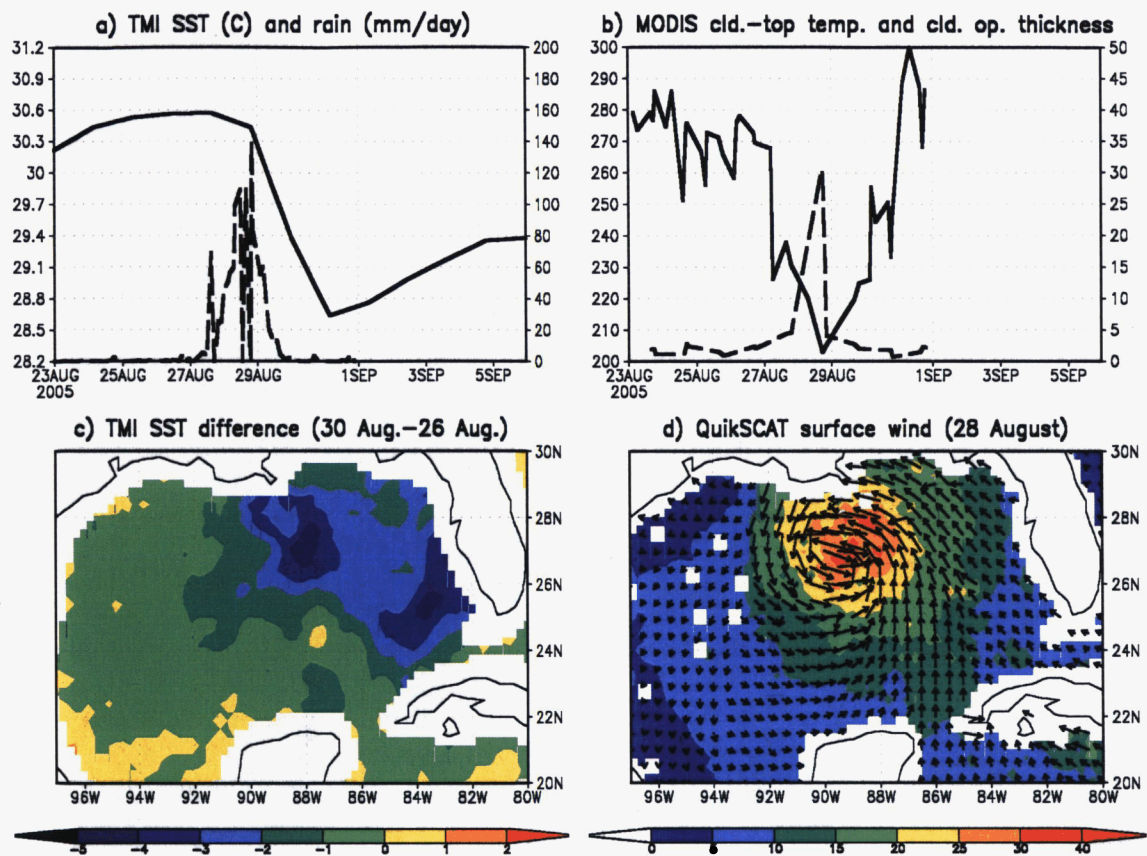
Figure 2: (a) Time series of TMI-derived daily SST (°C, solid line) and hourly microwave rain retrievals (mm/day, dashed line) averaged between 24°N-29°N, and 92°W–85°W; (b) Time series of MODIS cloud-top temperature (°K, solid line) and cloud optical thickness (dashed line) averaged between 24°-29°N and 92°–85°W; *(c)* SST difference (°K) before and after the passage of Hurricane Katrina; (d) QuikSCAT daily ocean surface wind speed (m/s) and wind vectors on 28 August 2005.
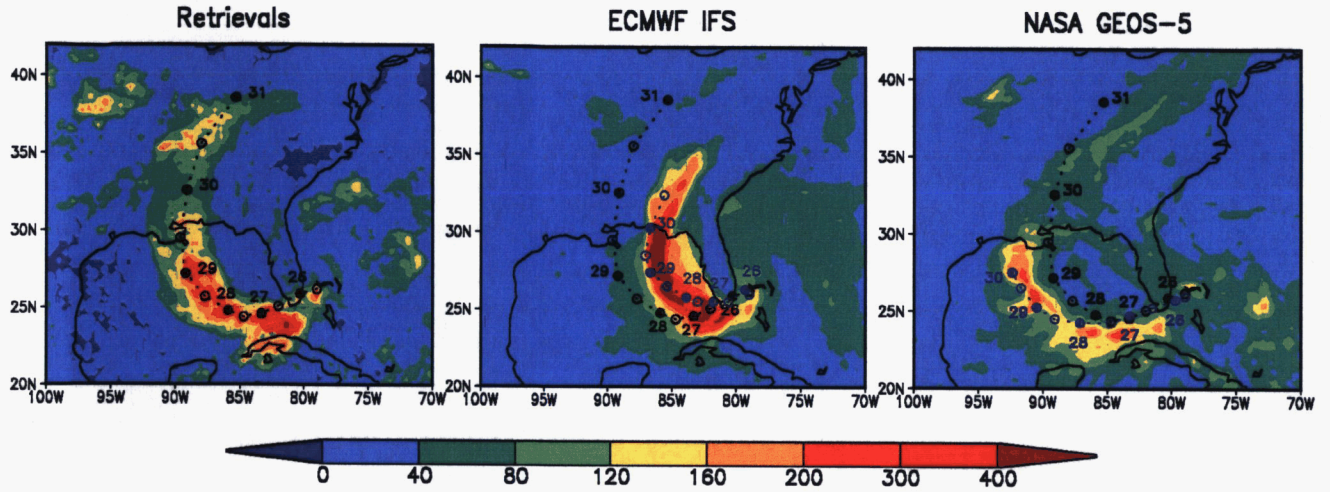
Figure 3: Accumulated 5-day surface rainfall (mm) from satellite retrievals, and from single forecasts by the ECMWF IFS and the NASA GEOS-5 high-resolution global models. The official NOAA observed "best track" (black line) and the forecast tracks (blue line) for Katrina are superimposed. The solid circles represent positions at 00Z, while the open circles represent positions at 12Z. The ECMWF and NASA forecasts are initialized at 12z and 06z, 25 August 2005, respectively.
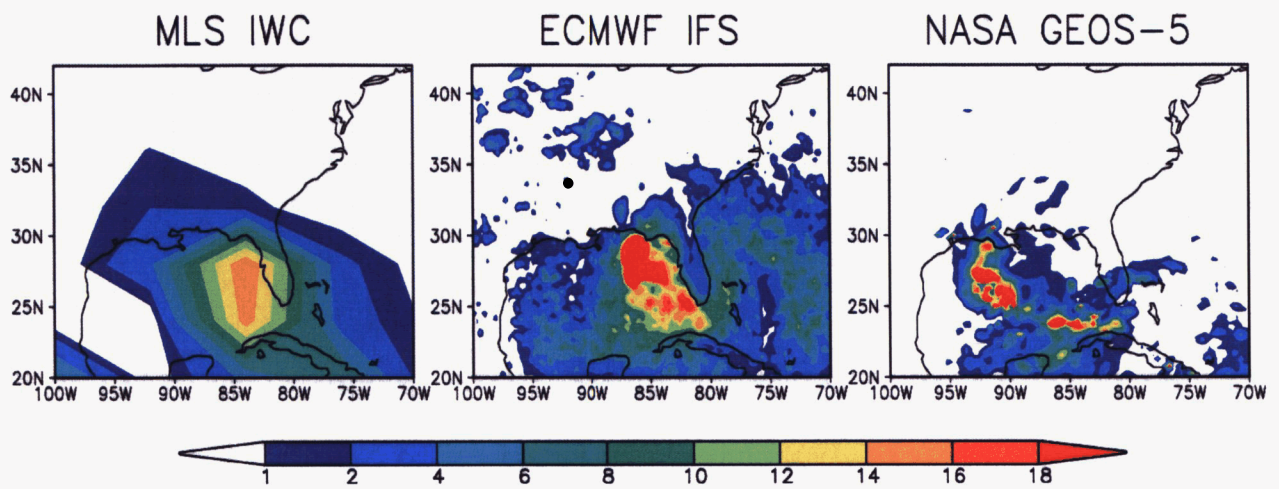
Figure 4: Similar to Figure 3 but for accumulated 5-day cloud ice water content (mg/m$^3$) at 147 hPa from EOS MLS, and from single forecasts by the ECMWF IFS and the NASA GEOS-5.